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Analysis of speed, stroke rate, and stroke distance for world-class breaststroke swimming

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Abstract

Speed in aquatic locomotion is determined by stroke distance and stroke rate, but it does not always follow that an increase in stroke rate will lead to an increase in speed. Kleshnev (2006) developed a method to evaluate the relationship between speed and stroke rate during rowing – the effective work per stroke. In this case study, the effective work per stroke was determined for a male world-class 100-m breaststroke swimmer for seven races in major championships and compared between: each of the seven races; each quarter within each race; and the best swims of this case study and seven other world-class swimmers. The effective work per stroke was related to race performance, with the fastest race having the highest effective work per stroke and lowest stroke rate, with slower races having low effectiveness and high stroke rate ($R^2 = 0.85$). The effective work per stroke was reduced in a race as the swimmer fatigued. The within-race standard deviation of effectiveness was lower in fast swims ($R^2 = 0.84$). This analysis has identified some characteristics of fast swimming: high effectiveness, optimal stroke rate, and a flat effectiveness profile. Training and racing strategies can now be devised to improve performance by increasing the sensitivity of assessment of strengths and weaknesses in individuals.

Keywords: *Swimming, stroke rate, stroke distance, effective work per stroke*

Introduction

Mean speed, stroke rate, and stroke distance are fundamental variables of aquatic locomotions such as swimming, rowing, and canoeing. Relationships between these variables are defined by several factors. The most obvious is athletes' anthropometry (Keskinen, Tilli, & Komi, 1989; Pelayo, Sidney, Kherif, Chollet, & Tourny, 1996). In general, taller and bigger athletes can produce more work per stroke, and therefore their stroke distance is longer. Smaller athletes cannot achieve such a long stroke distance, so they have to use higher stroke rates to compete with others.

The type of training is another factor that affects the relationship between stroke rate and stroke distance. An emphasis on aerobic and strength training, and on improvement of technique, produces a greater distance per stroke (Wakayoshi, Yoshida, Ikuta, Mutoh, & Miyashita, 1993). Speed and speed-endurance training methods can help athletes to sustain higher stroke rates, but the distance per stroke is shorter (Ebben et al., 2004).

If we want to achieve the top performance, we can ignore neither stroke rate nor distance per stroke. Therefore, assessment of these variables for each athlete in training and competition plays an important role. Speed of locomotion, V, is a product of the stroke rate, SR, and distance per stroke, SD, and can defined through the duration of the stroke cycle, T:

$$\begin{aligned} V &= SD/T \\ &= SD \cdot SR/60 \end{aligned} \tag{1}$$

Equation (1) can be rewritten for the distance per stroke, SD:

$$\begin{aligned} SD &= V \cdot T \\ &= 60\ V/SR \end{aligned} \tag{2}$$

This means that stroke rate and distance per stroke are inversely proportional at constant speed. When athletes increase stroke rate, distance per stroke is always reduced, because the duration of the cycle is shorter. Often, coaches ask athletes to maintain constant stroke distance at higher stroke rates, which means that speed must be increased proportionally to the stroke rate, which never happens in practice.

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Some authors (Keskinen et al., 1989; Pyne & Trewin, 2001) used an index I equal to product of the speed V and SD as a measure of stroke efficiency:

$$\begin{aligned} I &= V \cdot SD \\ &= 60\ V^2/SR \\ &= SD^2\ SR/60 \end{aligned} \tag{3}$$

The units for this index are $m^2 \cdot s^{-1}$, which has no physical meaning. It has little practical application, because it always reduces with an increase in the stroke rate.

Since we were unable to find any adequate method for evaluation of the relationship between stroke rate and stroke distance in aquatic locomotion in the literature, our aim was to redress this.

Methods

Biomechanical modelling

The relationship between hydrodynamic drag resistance force F_d, speed V, and external power generated by the athlete P in such aquatic sports as swimming (Huub, Paulien, & Kolmogorov, 2004) and rowing (Baudouin & Hawkins, 2002) can be defined as:

$$F_d = k \cdot V^2 \tag{4}$$

$$\begin{aligned} P &= V \cdot F_d \\ &= k \cdot V^3 \end{aligned} \tag{5}$$

where k is some dimensionless drag resistance factor, which depends on the type of locomotion, characteristics of the athlete, and pool conditions. The effective work per stroke, $eWPS$, can be expressed in terms of power P, time of stroke cycle T, speed V, and stroke rate SR:

$$\begin{aligned} eWPS &= P \cdot T \\ &= k \cdot V^3\,(60/SR) \\ &= 60k\,(V^3/SR) \end{aligned} \tag{6}$$

If, at two stroke rates (R_0 and R_1),

- drag resistance factors are equal ($k_1 = k_2$), which should be the case in the same athlete in the same conditions, and
- values of $eWPS$ are equal ($eWPS_0 = eWPS_1$),

then, using equation (6), we can derive the following equation:

$$60k\left(V_1^3/SR\right) = 60k\left(V_2^3/SR_2\right) \tag{7}$$

After simplifications, we can derive the ratio of the speeds V_0 and V_1 for these sections as follows, where V_0 is a baseline value. The baseline value is the mean of all the samples used in the comparative analysis – that is, each discrete race or each discrete sector within a race.

$$V_1/V_0 = (SR_1/SR_0)^{1/3} \tag{8}$$

To use equation (8) we do not need to know factor k, because we assume that it is the same for the two sections and so it cancels out. However, this is applicable only for the same athlete and the same pool conditions, which is a limitation of the method.

The most practically convenient implication of the method is the definition of "model" values of speed V_m and distance per stroke SD_m for a range of SR_m:

$$V_m = V_0(SR_m/SR_0)^{1/3} \tag{9}$$

For each of the samples, $eWPS$ can then be expressed relative to this baseline by taking ratios of the real values V_i to the "model" values:

$$eWPS\ (\%) = 100\ (V_i - V_m/V_m) \tag{10}$$

This model assumes constant effective work per stroke over this range of stroke rates, and so a swimmer will only achieve model values in reality if their effectiveness does not change when their rate changes.

Data analysis

Data were taken from 14 high-quality long-course men's 100-m breaststroke performances. Video footage and race information provided by competition organizers, broadcast media, and attendant sport scientists were used.

Races were suitable for analysis only if data were available for the "free swim" sections of the race – that is, excluding the start (15 m), turn (5 m in, 10 m out), and finish (5 m). These 14 performances included the best performances of seven of the top swimmers in the world for whom data were available from open-access sources such as the website of the international governing body, FINA (www.fina.org). The other seven performances were championship races from one world-class swimmer (Table I). He gave written informed consent, according to the guidelines of the institutional review board, that his race results could be analysed in the way detailed in this paper.

The data were analysed in two main ways, allowing comparisons of effectiveness:

1. Between each of the seven races for the case study, taking each race as a whole. This was

done separately for (a) all of the case study races and (b) for all of the top eight performances.

2. Between sectors in each race, for all of the case study races. The sectors were the free-swim portions of each quarter of the race, and were therefore taken as the splits from 15 to 25 m, 25 to 45 m, 60 to 75 m, and 75 to 95 m.

The "model" speed values were calculated using equation (9). The mean value of V for each set of samples was taken as the baseline value V_0.

Results

"Model" values were plotted together with the real data relative to the stroke rate (Figure 1). Real-data *eWPS* are percentage differences from model values, and so real data lying above the model line result in positive values for effective work per stroke and those below the line in negative values. The effective work per stroke for each of the case study's races is shown in Figure 2a, which demonstrates that effectiveness reduced over time.

This decrease in effectiveness was coincident with a decrease in mean race speed (Figure 2b) and an increase in stroke rate (Figure 2c). That is, this swimmer swam slower at higher stroke rates, which can also be seen in the correlation between speed and stroke rate in Figure 1.

For all races, effectiveness decreased in a race as the swimmer became fatigued (Figure 3). Also, successful (faster) races were characterized by a flatter effectiveness profile. That is, the within-race standard deviation of effectiveness was lower in fast swims ($R^2 = 0.84$), showing that effectiveness was better maintained to the finish. This can also be demonstrated by visual inspection of the profiles of the fastest race (race 1), where speed was $1.564\ \text{m} \cdot \text{s}^{-1}$ ($s = 3.4\%$), and the slowest race

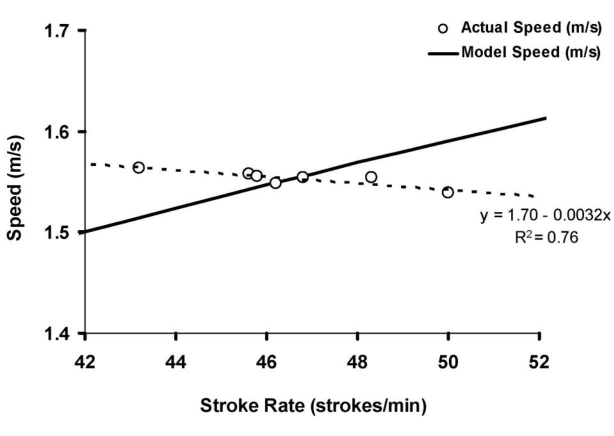

Figure 1. "Model" data (solid line) together with real race data (open circles) for our case-study swimmer's seven races (see Table I for full list of races). The baseline speed was set at the mean of these seven races, which was $1.553\ \text{m} \cdot \text{s}^{-1}$ at a stroke rate of 46.6 strokes per minute. The dashed line is a linear fit to the real data, demonstrating a negative correlation between speed and stroke rate ($R^2 = 0.76$). Real data lying above the model's solid line indicate that the swimmer was more effective than the mean, and data below the solid line indicate that the swimmer was less effective than the mean.

Table I. Races used in the case study.

1 and 2:	World Championship semi-final and final 2005
3 and 4:	Commonwealth Games semi-final and final 2006
5 and 6:	European Championship semi-final and final 2006
7:	World Championship semi-final 2007

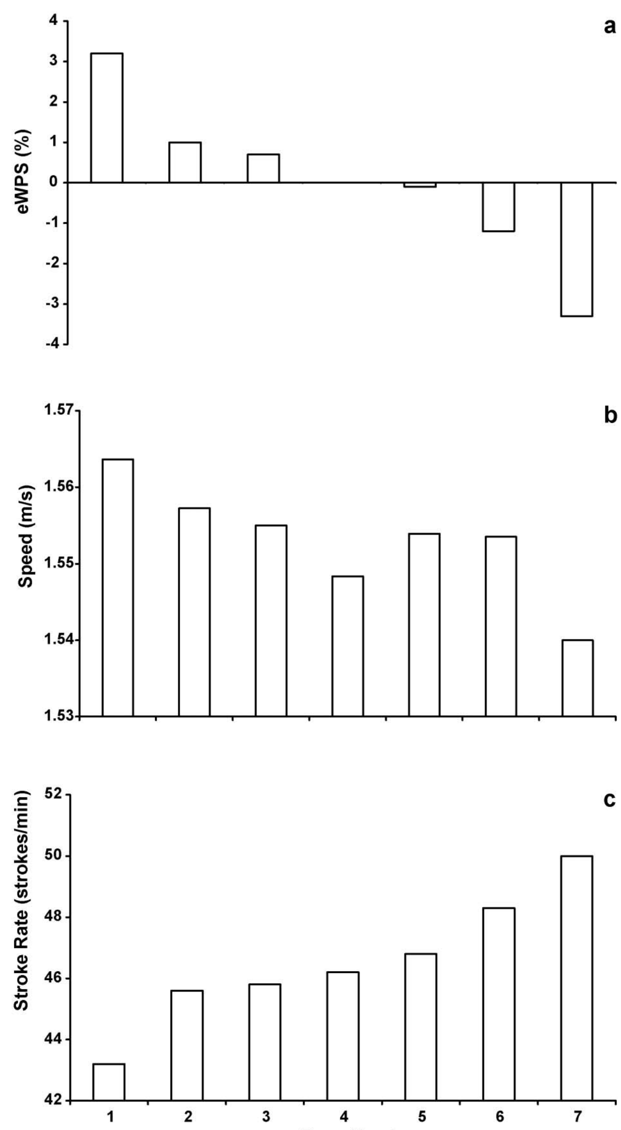

Figure 2. Effectiveness (a), swim speed (b), and stroke rate (c) for our case-study swimmer's seven races (see Table I for the full list of races).

(race 7), where speed was 1.540 m · s^{-1} ($s = 7.6\%$) (Figure 3).

There was no correlation between effective work per stroke and swim speed when the best performances of eight of the top swimmers in the world were compared ($R^2 = 0.01$; Figure 4).

Discussion

In this paper, we have derived a new index to assess swimming stroke effectiveness, and then use this index to analyse performances in the men's 100-m breaststroke event. This is the first time that the

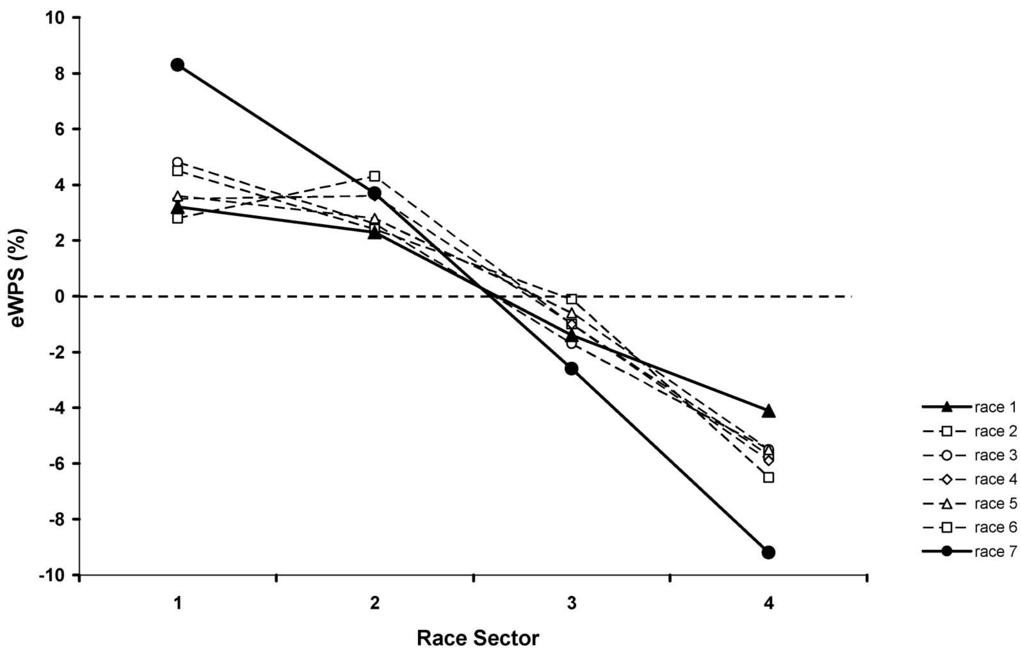

Figure 3. Within-race effectiveness for our case-study swimmer's seven races; each race is represented by one line. The standard deviations of the within-race effectiveness for each race were, in order from race 1 to race 7: 3.4%, 4.5%, 4.6%, 4.5%, 4.1%, 4.8%, and 7.6%.

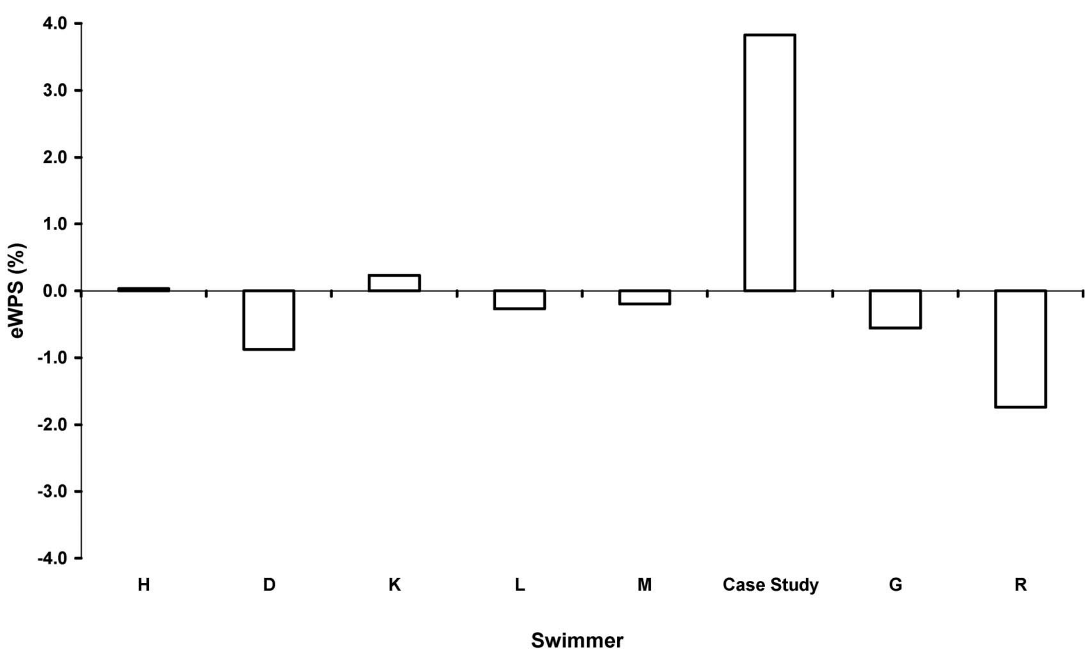

Figure 4. Whole-race effectiveness for our case-study swimmer's best race, compared with those of seven other world-class swimmers. Swimmers are arranged in order of descending speed.

derivation of the effective work per stroke (eWPS) has been published outside of conference proceedings (Kleshnev, 2006) and online (www.biorow.com), where its use has been described for rowing. This is the first time that this index has been used to analyse swimming performance.

The eWPS index was strongly related to overall race performance (Figure 2). That is, the more effective the stroke, the faster the time achieved, with the fastest races having the highest eWPS index. It should be noted that this case study showed a strong *chronological* trend to swim slower and less effectively (Figure 2). That is, over a 2-year period the swimmer has gradually been getting slower, culminating in missing out on a major final for the first time at the 2007 World Championship. This problem is discussed later.

Effectiveness analysis also helped to explain successful and unsuccessful swims, as demonstrated by the within-race data shown in Figure 3; a successful race is one where effectiveness is well maintained throughout the race. Analysis of race execution when a slower time was achieved revealed that, for the present case study, slow swims coincided with a low effective work per stroke and high stroke rate. In this case, the decrease in effectiveness is obvious: the swimmer took more strokes at a higher frequency, yet swam slower. This validates the eWPS concept, which demonstrates the relationship between speed and rate as a single index.

This analysis allows us to suggest three possible interventions that are likely to result in an improvement in performance for our case-study swimmer. First, as there is a strong correlation between effectiveness profile variation and swim speed, it is important to maintain effectiveness throughout the race (Figure 3). Part of this could be achieved by conditioning – minimizing fatigue and maintaining a good technique over the closing stages of the race. This could be a tactical or psychological component; for example, not setting off too quickly (the gains on the first length will be punished in the final 25 m) and making a conscious effort to produce long strokes in the final 25 m rather than increasing the rate and "spinning" (i.e. losing effectiveness and losing speed).

A second piece of race strategy advice is to race at the low end of the range of stroke rate seen here. This puts the swimmer at a lower rate than most of his international rivals; the other seven swimmers analysed showed a mean rate of 49 strokes per minute (range 46–51) compared with our swimmer's optimal rate of 44 strokes per minute. It is clear that without the depth of analysis presented here, this observation might have resulted in our swimmer being advised to increase his rate to make him more like the other swimmers. However, it is now clear that this does not apply to this particular individual and he should resist any temptation to conform to precedents set by his competitors.

A final piece of advice is to implement a training programme that maximizes the swimmer's effectiveness at his desired racing stroke rate. This could include an increase in the volume of swimming performed at this rate so as to develop physical and technical components required to produce long strokes and good speed. Since he has a lower stroke rate than his rivals, he might also benefit from land-training that puts the emphasis on developing high forces during slow movements.

The eWPS method relies on an immeasurable unknown (k in equation 5) being constant in the different conditions compared. Constant k is related to pool conditions, which we can assume to be stable across races, but it is also related to the technique adopted and drag forces experienced by an individual swimmer. These probably change at different stroke rates and speeds for the same swimmer, and are highly likely to be different across swimmers. These are limitations to be aware of, although the eWPS index appears to be robust to these possibly small effects.

The data presented in Figure 4 indicate that we should be aware of these limitations when comparing swimmers, as the fastest swimmers were not necessarily the ones with highest effective work per stroke. This comparison is meaningful in our case study, as the swimmer is small in stature yet takes long strokes. He has a technical quality that produces exceptionally effective strokes at low stroke rate. This contradicts our statement in the Introduction that taller athletes tend to produce longer strokes and that smaller athletes have to use higher stroke rates to compete with others. It is exciting to imagine how fast our participant could swim if he could maintain this effectiveness at high, or even mean, rates. This observation begs a modification to the intervention suggested above: training should be centred on producing effective strokes at, say, 46 strokes per minute.

We should also be careful when we use the term "effective work per stroke". This term should not be understood to imply that we are measuring or trying to measure work per stroke in the true mechanical sense, as desirable as that would be. This index does not allow us to evaluate external or internal work, or active or passive drag in any way. Instead, this analysis attempts to provide *ratios* of effective work per stroke as the resultant parameter. Another limitation could be our simplified use of the term "power" where "impulse" might strictly be more appropriate. However, we have shown that despite these limitations, this index appears to be a valid application.

This new index is a notable improvement on the only previous widely used index *I* (Keskinen et al., 1989, Pyne & Trewin, 2001), which, since its dimensions are $m^2 \cdot s^{-1}$, has little physical meaning. The index *I* is easy to calculate and behaves predictably: it decreases with a concomitant increase in stroke rate. This predictability is, however, one of its shortcomings, because it can reveal only the obvious, whereas we have demonstrated here the ability of the effective work per stroke to detect more subtle patterns.

This analysis has identified characteristics required for fast swimming, both for world-class swimmers in general and our case-study swimmer in particular. These characteristics include high effectiveness, a flat effectiveness profile through the race, and an optimal stroke rate. Training and racing strategies can now be devised to improve performance by increasing the sensitivity of assessments of strengths and weaknesses in individuals. If training interventions are successful, then we should be able to measure an increase in effective work per stroke, see a flatter profile across the four sectors of the 100-m race, with a much improved fourth sector because of a better-executed first 75 m.

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